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Gamma-Ray Observations of Starburst Galaxies

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Abstract

The supernova rate in starburst galaxies has been estimated to be on the order of ten to twenty times the supernova rate in our Galaxy. If the dominant acceleration sites of cosmic rays are supernova remnants then the cosmic ray density in starburst galaxies should also be proportionally higher. This implies that the diffuse gamma-ray emission from starburst galaxies can be used to directly estimate the cosmic ray density in these objects. Data from EGRET gamma-ray observations of the nearby starburst galaxies M82 and NGC 253 for CGRO cycles 1 through 4 (1991 April through 1995 October) has been analyzed using point-source likelihood techniques. The results of this analysis are presented.

INTRODUCTION

The all sky survey by the Compton Gamma-Ray Observatory during the period 1991 April - 1995 October has led to the detection of a number of high-energy gamma-ray sources with the Energetic Gamma-Ray Experiment Telescope (EGRET). EGRET covers the high-energy gamma-ray range from approximately 30 MeV to 30 GeV. This survey is also being examined for the existence of emission from normal galaxies, which is expected from the interaction of relativistic particles and interstellar matter and photons. The Large Magellanic Cloud (LMC) has been detected at a level consistent with its galactic cosmic ray density being at about the expected level (Sreekumar et al. 1992), and an upper limit to the flux from the Small Magellanic Cloud (SMC) has shown that the cosmic rays are not metagalactic and provided additional evidence that the Small Magellanic Cloud may be in a state of disruption (Sreekumar et al. 1993).

Other relatively close galaxies are also of interest in relation to the level of their gamma-ray emission. Gamma ray observations provide a direct way to examine the cosmic ray distributions in external galaxies. Above a few hundred MeV diffuse gamma ray emission primarily arises from the decay of neutral pions resulting from proton-proton interactions. While relativistic electrons can be studied using radio observations, cosmic ray protons, which carry most of the energy in cosmic rays, are best studied using high-energy gamma-ray observations. NGC 253 and M82 are the nearest starburst galaxies. Their high star formation rate (SFR) and supernova rate (SNR) (10 to 30 times the Milky Way SNR) could result in high cosmic ray densities. Using radio continuum data, it is estimated that the energetic electron density in the central part is well over an order of magnitude greater than that in our Local galactic region. If one assumes a typical proton to electron ratio as that in our Local region, this implies a nucleonic cosmic ray component well in excess of that in our galactic neighborhood. Gamma ray observations can provide new opportunities to examine the relationship between SFR, SNR and cosmic rays in starburst galaxies.

With these considerations in mind, the EGRET high-energy gamma-ray data from the directions of these two galaxies were examined thereby updating the earlier work of Sreekumar et al. (1994). The results are reported in this paper, together with a discussion of their implications.

RESULTS AND DISCUSSION

NGC 253 and M82 are the nearest starburst galaxies, at a distance of 2.5 and 3.3 Mpc, respectively. They are typical starburst galaxies, characterized by an unusually high star formation rate, and have been extensively studied from radio to X-rays. They are bright infrared objects ($L_{FIR} \sim 1 \times 10^{44}$ ergs s^{-1}) and exhibit extended X-ray and radio emission. Bartel et al. (1987) estimated the supernova rates to lie in the range of (0.1-0.3) per year, about 10 to 30 times the generally assumed rate in the Milky Way. Being the nearest starburst galaxies, they are interesting candidates to examine for high-energy gamma-ray emission from such systems.

NGC 253 is the nearest (barred) spiral outside the local Group, with a bright central region in the infrared, X-rays and radio frequencies. Krugel et al. (1990) compared the estimated mass of the interstellar gas in the central regions of NGC 253 and M82 and concluded that the higher gas density in NGC 253 could be indicative of it being at an earlier stage of star burst evolution. Rieke, Lebofsky and Walker (1988) estimate a supernova rate of 0.1 yr^{-1} in the central 50 pc. At infrared and optical wavelengths, the central bar extends about 3.5 kpc from the nucleus. Canzias, Mundy and Scoville (1988) observed a molecular gas counterpart to the stellar bar and derived the total molecular mass to be about 4.8×10^8 $M_\odot$. Puche, Carignan and van Gorkom (1991) determined the total H_I mass to be about 9×10^9 $M_\odot$. Assuming a mean cosmic ray energy density range of 10 to 100 times the energy density derived in our local Galactic region, the expected gamma ray flux above 100 MeV is estimated to range from 0.02 to 0.2×10^{-7} photons $cm^{-2}s^{-1}$ respectively. Comparing this to observations, 0.63×10^9 cm^2s of EGRET exposure on NGC 253 give a 2σ upper limit on the integral flux above 100 MeV of 0.7×10^{-7} photons $cm^{-2}s^{-1}$. This is significantly above the expected flux even with the extremely optimistic estimate of the cosmic ray density.

Analysis of 1.7×10^9 cm^2s of EGRET observation of M82 yields a 2σ upper limit of 0.3×10^{-7} photons $cm^{-2}s^{-1}$. As in the case of NGC 253, the expected diffuse gamma ray emission from M82 can be calculated from a knowledge of the total galactic mass in the form of interstellar gas and assuming a mean cosmic ray density in the galaxy. Numerous studies involving 21-cm and CO line emission provide details on the mass distribution in M82 (Olofsson and Rydbeck 1984; Young and Scoville, 1984; Nakai et al. 1987). The mean cosmic ray density is determined from radio continuum data, which provide a direct way to examine the nature and distribution of relativistic electrons. Radio maps of M82 shows strong emission along the major axis of the galaxy. Observations also show radio emission in directions normal to the disk (Seaquist and Odegard, 1991; Reuter et al. 1993) which indicate the presence of relativistic particles out to large distances (a few hundred parsecs) from the stellar disk, characterized by a steeper spectrum. The steeper spectrum could arise from synchrotron and inverse Compton losses as the electrons diffuse out of the disk. In addition, gas kinematics provides evidence for outflow from the central regions of M82 (William, Caldwell and Schommer, 1984). This is also consistent with CO observations indicating the presence of molecular gas up to several hundred parsecs from the disk. Hence, diffuse gamma ray emission may not be restricted to the disk and could extend out to large distances from the plane.

The mean energy density for relativistic electrons in the central region of M82 was estimated from radio data by Klein, Wielebinski and Morsi, (1988) using equipartition arguments, to be ~60 eV cm^{-3}. Volk, Klein and Wielebinski (1989) gave an estimate of 80 eV cm^{-3}. This is more than 3 orders of magnitude larger than the value determined in our local galactic neighborhood (6000 to 8000 times larger if local cosmic ray electron density is taken to be 0.01 eV cm^{-3}. Similarly the magnetic field strength of ~50 μG derived for M82 is about 10 times the local value. Assuming the standard value of the proton to electron ratio of 100 (Ginzburg and Syrovatskii, 1964), the significantly larger average cosmic ray energy density implies enhanced gamma ray production in the central region via nucleon-nucleon interaction and the electron bremsstrahlung processes. However, outside the central region the cosmic ray energy density decreases rapidly from the value in the central region and hence a corresponding drop in the gamma ray emission is expected.

Akyuz, Brouillet and Ozel (1991) calculated the expected diffuse emission from M82 using the approach as described above. They derived a mean cosmic ray energy density of ~22 eV cm^{-3} for the whole of M82 by averaging the cosmic ray energy density of ~60 eV cm^{-3} obtained for the central region with a mean density of 1 eV cm^{-3} elsewhere which is equal to the generally accepted value for our local Galactic region. At energies > 100 MeV their calculation yield a flux of 0.14×10^{-7} photons $cm^{-2}s^{-1}$. This is consistent with the upper limit derived from EGRET data.

CONCLUSION

EGRET observations of the nearby starburst galaxies NGC 253 and M 82 yield significantly lower upper limits on their high-energy gamma-ray emission than those of SAS-2 and COS-B. The derived upper limits are all consistent with the theoretically estimated values. These observations indicate that the extremely enhanced cosmic ray energy density derived from radio continuum data in the central region of these galaxies are not sustained everywhere in the galaxy. The gamma ray observations constrain the maximum permissible mean cosmic ray energy density to be below a few 100 times that observed in our Local galactic neighborhood, not sufficient to provide additional details on cosmic rays in starburst galaxies. Significant increases in exposure with EGRET or a more sensitive instrument are required to detect positive emission or significantly constrain existing models on cosmic ray densities in these external galaxies.

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